Full Length Research Paper

Adaptive fuzzy control for earthquake-excited buildings with lead rubber bearing isolation

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This study examines the feasibility of applying adaptive fuzzy sliding mode control (AFSMC) strategies to reduce the dynamic responses of buildings constructed using a lead rubber bearing (LRB) isolation hybrid protective system. Recently developed control devices for civil engineering structures, including hybrid systems and semi-active systems, have been found to have inherent nonlinear properties. It is thus necessary to develop non-linear control methods to deal with such properties. Generally, controller fuzziness increases the robustness of the control system 75 to counter uncertain system parameters and input excitation, and the non-linearity of the control rule increases the effectiveness of the controller relative to linear controllers. AFSMC is a combination of sliding mode control (SMC) and fuzzy control. The performance and robustness of these proposed control methods are all verified by numerical simulation. The results demonstrate the viability of the presented methods. The attractive control strategy derived there-from is applied to seismically excited buildings using LRB isolation.

Key words: Lyapunov theory, adaptive fuzzy sliding mode control, lead rubber bearing (LRB).

INTRODUCTION

The theory of structural control has been proposed as a means to protect the safety and integrity of structures. Control schemes can be divided into roughly three types, passive, active and hybrid. Hybrid control methods, which possess the advantages of both passive and active control systems, have recently received considerable attention (Housner et al., 1997). In particular, hybrid protective systems comprised of a combination of passive base-isolation systems and active control devices, as shown in Figure 1, have been shown to be quite effective in reducing structural responses to strong earthquakes. Several base-isolation hybrid protective systems exist. These include lead rubber bearings (LRBs) and actuators, LRBs and variable dampers, and frictional sliding bearings and actuators.

Currently, elastomeric bearings are the most widely used of the common LRB isolation systems. The elastomer is made of either natural rubber or neoprene, as shown in Figure 2. The bearings are formed by vulcanization bonding of sheets of rubber to thin steel reinforcing plates. The bearings are extremely stiff in the vertical direction but highly flexible in the horizontal direction. This approach works by interposing a layer with low horizontal stiffness between the building and the foundation which decouples the building motion from the horizontal components of the earthquake ground motion.

The disadvantage of LRB isolation is the possibility of damage to the bearings or the superstructures resulting from large lateral displacement. Hybrid control aims to exploit the advantages of both active and passive control systems. The LRB isolation system is used to reduce the inertial loading transmitted by the ground motion to the building, while active control devices are used to reduce the response of the superstructure. The dynamic behavior of LRB isolation systems can be either highly nonlinear or inelastic. Nonlinear systems require a nonlinear control method. The concept of structural control in civil engineering applications originated in the early 1970s (Yao, 1972). Some commonly used structural control methods include LQR optimal control (Yang, 1975), pole assignment (Abdel-Rohman et al., 1981), and instantaneous optimal control (Yang et al., 1987). Recently, other methods such as H_2 (Suhardjo et al., 1992) H_∞ (Schmitendorf et al., 1994) optimal control, sliding-mode control (Yang et al., 1995),
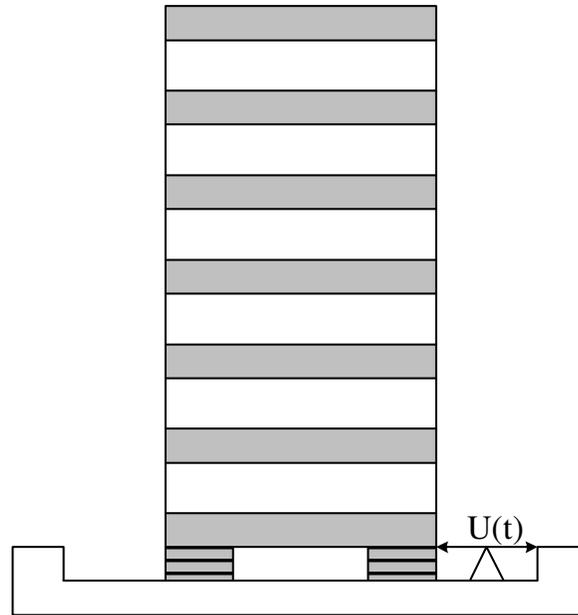
Figure 1. An based-isolated.
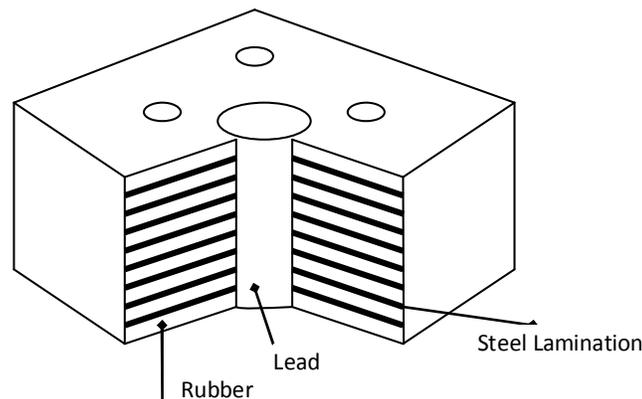
Figure 2. Lead rubber bearings (Skinner et al., 1993).

LQG/LTR (Lu et al., 1998), fuzzy control (Yeh et al., 1996), and fuzzy sliding mode control (Alli and Oguz, 2005, 2007) have been introduced to deal with structural control problems.

In this study, an adaptive fuzzy sliding mode control method is proposed for the structural control of buildings with LRB isolation. Systems with complex mechanisms, such as are commonly found in the industrial sector, that are non-linear, and/or ill-defined, are difficult to model mathematically, but can be adequately controlled and operated in real world situations. Operator control strategies for such systems, are developed based on intuition and experience, and can be considered as comprised of a set of heuristic decision rules. Fuzzy set theory and fuzzy algorithms can be used to directly and

effectively assess such imprecise linguistic statements. However, fuzzy control design still involves several difficulties: (1) the large number of fuzzy rules required for multi-dimension systems make analysis very complex; (2) suitable parameters must be determined for the membership functions using a time-consuming trial and error procedure; (3) no stability analysis tools can be applied to fuzzy control systems (Lo et al., 1998). In order to solve these problems, Chen et al., (2007) Chen (2006), Hsiao et al. (2005), Liu et al. (2010) and Yeh et al., (2008) proposed a stability condition for a nonlinear structural system based on both linear matrix inequality (LMI) transformation and the T-S fuzzy model. Although, the controller design problem can be transformed into a solvable LMI problem, the control

approach has to be enhanced to be effective for real engineering applications. Here, we consider adaptive fuzzy sliding mode control (AFSMC) strategies for a real building structure with an LRB isolation hybrid protective system.

Generally, even if the system parameters are difficult to define precisely, the bounds on the uncertain parameters may be known. It is certain that sliding mode control is useful for uncertain and nonlinear dynamic systems (Hui et al., 1992). This approach can systematically solve the problem of maintaining stability and consistent performance. Yager et al. (1994) determined some fuzzy rules based on the sliding mode condition. The sliding surface can dominate the dynamic behaviors of the control system and reduce the number of rules in the fuzzy rule base. Palm (1992) demonstrated that fuzzy control can be considered an extension of the conventional sliding mode controller with a boundary layer. Adaptive fuzzy control (Wang, 1993; Wang, 1994) uses a linear combination of fuzzy basic functions. The consequent parameters are tuned via an adaptive mechanism. The adaptive law for the method of adaptive fuzzy sliding mode control presented in this study is derived from the Lyapunov theory. The adaptive law is used to tune the centers of the consequences of the membership functions. A stable adaptive fuzzy sliding mode control is developed for affine highly nonlinear systems (Hwang et al., 2001). The desired control behavior is achieved by developing an equivalent control using the unknown part of the system dynamics and the fuzzy learning model. Lhee et al. (2001) described sliding mode-like fuzzy logic control with fast self-tuning of the dead-zone parameters given parameter variations in the controlled system.

Fischle et al. (1999) extended the method of stable adaptive fuzzy control to a broader group of nonlinear plants. They achieved this by using an improved controller structure adopted from the neural network domain. Their controllers (Palm, 1992; Lhee et al., 2001; Fischle et al., 1999) were designed for application to a high order single output system. However, since civil structures are multi-output systems, the response information from sensors may include a wide variety of data such as displacements, velocities and accelerations. The coefficients of the sliding surface (Palm, 1992; Hwang et al., 2001; Lhee et al., 2001; Fischle et al., 1999) are selected so that s(t) = 0 is Hurwitz. In this study, the optimal sliding mode method is used to determine the sliding surface. The controller's sliding surface (Palm, 1992; Hwang et al., 2001; Lhee et al., 2001; Fischle et al., 1999) can ensure system stability. Notably, the optimal sliding mode method not only ensures system stability, but can also adjust the weighting matrices according to the control objective. The method discussed in this paper is more efficient than other types of controllers (Palm, 1992; Hwang et al., 2001; Lhee et al., 2001; Fischle et al., 1999). The aim of this study is thus to develop a systematic AFSMC design procedure capable of controlling the behavior of seismically excited buildings constructed with LRB isolation systems. The effectiveness of the developed algorithm is illustrated using several examples applied to LRB isolated buildings.

Equation of motion for the structural system

The equation of motion for a building modeled by an n-degrees-of-freedom system controlled by actuators and subjected to ground excitation $\ddot{x}_g$ can be expressed as follows:

$$M\ddot{Z}(t)+C\dot{Z}(t)+KZ(t)+\overline{H}\,f(t)=\overline{B}\,U(t)\text{-}M\overline{r}\,\ddot{x}_g \tag{1}$$

where $Z=[x_1,x_2,...x_n]^T \in R^n$ = n-vector; and x_i denotes the relative displacement of the designed ith element. Matrices M, C, and K=n×n represent the mass, damping, and stiffness matrices, respectively; $\overline{r}$ = n-vector is the influence of the earthquake excitation; $\overline{H}$ = n-vector denotes the locations of the isolators; and $\overline{B}$ =n×m matrix represents the locations of the m control forces. The m-dimensional control force vector U(t) corresponds to the actuator forces (which are generated via an active tendon system or mass damper, for example); and f(t) is the force from the isolators.

The hysteretic stiffness of an isolator can be modeled by Yang et al., (1992).

$$F_{sb}=ak_bx_b+(1\text{-}a)k_bD_yv \tag{2}$$

where F_{sb} denotes the stiffness of the isolator; a represents the ratio of the post yielding to pre-yielding stiffness; k_b is the elastic stiffness of the isolator; x_b denotes the isolator displacement; D_y represents the yielding deformation; and v is the hysteretic variable, where:

$$v^{'}(t) = D_y^{-1}(\alpha x_b^{'} - \beta \left| x_b^{'} \right| \left| v \right|^{\eta-1} v - \gamma x_b^{'} \left| v \right|^{\eta}) \tag{3}$$

Parameter α, β, γ and η determine the scale, general shape, and smoothness of the hysteretic loop, respectively.

In Equation (2), ak_bx_b denotes the linear elastic stiffness that appears in the K matrix of Equation (1). The nonlinear or hysteretic stiffness appearing in the nonlinear or hysteretic, f of Equation 1 is thus expressed by:

$$f(t)=(1\text{-}a)k_bD_yv \tag{4}$$

For this controller design, the standard first-order state equation corresponding to Equation (1) is

$$\dot{X}(t)=AX(t)\text{-}Hf(t)+BU(t)+L\ddot{x}_g \tag{5}$$

where $X^T=[Z^T \quad \dot{Z}^T]$ =2n vector; and

$$A=\begin{bmatrix} 0 & I_{n\times n} \\ -M^{-1}K & -M^{-1}C \end{bmatrix}, \quad H=\begin{bmatrix} 0 \\ M^{-1}\overline{H} \end{bmatrix}$$

$$B=\begin{bmatrix} 0 \\ M^{-1}\overline{B} \end{bmatrix}, \quad L=\begin{bmatrix} 0 \\ -\overline{r} \end{bmatrix} \tag{6}$$

Adaptive fuzzy sliding mode control

Design of the sliding surface

The complete account of the sliding mode control theory is seen in Decarlo et al. (1988) and Utkin (1992). This theory is based on the concept that the controller changes its structure according to the position of the state trajectory with respect to a selected sliding surface. The control is designed to force the state trajectory of the system onto the sliding surface and maintain it there. This is achieved with a high speed switching law. This discontinuous component of the sliding control is used to develop fuzzy logic control.

The design of the sliding surface is detailed subsequently. The equation of the system has the form

$$\dot{X} = AX + BU + F + E \tag{7}$$

where $X(t)$ denotes an n state vector; A represents an n×n system matrix; B is an n×m controller location matrix; F denotes an n vector containing the system uncertainty and nonlinearity; and E is an n excitation vector.

Suppose { x | S(X) = 0 } is the selected sliding surface.

$$S(X) = PX \tag{8}$$

where P is an m×n sliding surface coefficient matrix.
Consider the nominal system (Hsiao et al., 2005)

$$\dot{X} = AX + BU \tag{9}$$

From which we obtain the sliding surface of the nominal system. First, the state equation of motion (Equation 9) is converted into the so-called regular form via the following transformation:
Let;

$$Y = JX \text{ or } X = J^{-1} Y \tag{10}$$

where J is a transformation matrix

$$J = \begin{bmatrix} I_{n-m} & -B_1 B_2^{-1} \\ 0 & I_m \end{bmatrix}, \quad J^{-1} = \begin{bmatrix} I_{n-m} & B_1 B_2^{-1} \\ 0 & I_m \end{bmatrix} \tag{11}$$

and where B_1 and B_2 are the (n-m)×m and m×m submatrices obtained by partitioning the B matrix, as in Equation (9), as follows:

$$B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \tag{12}$$

Matrix B_2 should be nonsingular.
With the transformation J, the state Equation (7), and the sliding surface (Equation 8).
Hence

$$\dot{Y} = \overline{A} Y + \overline{B} U$$
$$S = \overline{P} Y \tag{13}$$

where $\overline{P} = PJ^{-1}$, $\overline{A} = JAJ^{-1}$, $\overline{B} = \begin{bmatrix} 0 \\ B_2 \end{bmatrix}$.

Let $Y = \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix}$; $\overline{A} = \begin{bmatrix} \overline{A}_{11} & \overline{A}_{12} \\ \overline{A}_{21} & \overline{A}_{22} \end{bmatrix}$; $\overline{P} = \begin{bmatrix} \overline{P}_1 & \overline{P}_2 \end{bmatrix}$ (14)

where Y_1 and Y_2 are the n-m and m vector, respectively; and $\overline{A}_{11}$, $\overline{A}_{12}$, $\overline{P}_1$ and $\overline{P}_2$, are the (n-m)× (n-m), (n-m)×m, m×(n-m) and m × m matrices, respectively. Substituting Equation (14) into (Equation 13) we obtain the equations of motion on the sliding surface

$$\dot{Y}_1 = \overline{A}_{11} Y_1 + \overline{A}_{12} Y_2 \tag{15}$$

$$S = \overline{P}_1 Y_1 + \overline{P}_2 Y_2 = 0. \tag{16}$$

For simplicity, $\overline{P}_2$ is set to be an identity matrix, that is, $\overline{P}_2 = I_m$ and thus,

$$Y_2 = -\overline{P}_1 Y_1 \tag{17}$$

and

$$\dot{Y}_1 = (\overline{A}_{11} - \overline{A}_{12} \overline{P}_1) Y_1 \tag{18}$$

The $\overline{P}_1$ matrix can be calculated from (Equation 18) such that the matrix $Y = [Y_1^T \ Y_2^T]^T$ on the sliding surface is stable. The optimal sliding mode method is used to determine the $\overline{P}_1$ matrix and P is also obtained. The method for obtaining the optimal sliding mode (Yang et al., 1995) is described subsequently.
The sliding surface is derived by minimizing the integral of the quadratic function of the state vector

$$I = \int_0^\infty X^T Q X dt \tag{19}$$

Where Q denotes a (2n× 2n) positive definite weighting matrix. In terms of the transformed state vector Y, (Equation 19) becomes

$$I = \int_0^\infty \begin{bmatrix} Y_1^T & Y_2^T \end{bmatrix}^T T \begin{bmatrix} Y_1 \\ Y_2 \end{bmatrix} dt \tag{20}$$

where $T = (J^{-1})^T Q J^{-1}$; $T = \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix}$ (21)

and T_{11} and T_{22} are the (2n-m) × (2n-m) and (m × m)matrices, respectively.
Minimizing the performance index I subjected to the equations of motion (Equation 15) we obtain

$$Y2 = -0.5 T_{22}^{-1} (\overline{A}_{12} T \hat{P} + 2 T_{21}) Y1 \tag{22}$$

where $\hat{P}$ is a (2n-m) × (2n-m) Riccati matrix that satisfies the following matrix Riccati equation:

$$\hat{A}^T \hat{P} + \hat{P} \hat{A} - 0.5 \hat{P} \overline{A}_{12} T_{22}^{-1} \overline{A}_{12}^T \hat{P} = -2(T_{11} - T_{12} T_{22}^{-1} T_{12}^T) \tag{23}$$

where $\hat{A} = \overline{A}_{11} - \overline{A}_{12} T_{22}^{-1} T_{21}$ (24)

A comparison between Equations (17) and (22) indicates that

$$\overline{P}_1 = 0.5 T_{22}^{-1} (\overline{A}_{12}^{\ T}\hat{P} + 2T_{21}).$$ (25)

Finally, the sliding surface is obtained

$$P = \overline{P}\ J = [\overline{P}_1 \quad I_m]J$$ (26)

Design of an adaptive fuzzy sliding mode controller

The second step is to design the controller. The controllers are designed to drive the state trajectory into the sliding surface $S=0$. Define a Lyapunov function V such that

$$V = 0.5 S^T S$$ (27)

The sufficient condition for the sliding mode S=0 occurring as t $\to \infty$ is

$$\dot{V} = S^T \dot{S} < -\eta \|S\|$$ (28)

where η is a positive real value. In (Equation 7), F is an n vector containing the system uncertainty and nonlinearity, while E is an n excitation vector. Generally, it is difficult to know system parameters exactly, but the bounds on the uncertainty are knowable.

$$\|F\| \le \delta_F \quad, \quad \|E\| \le \delta_W$$ (29)

Let

$$U = U_{eq} - (\gamma+\eta)sgn(S^T PB)^T$$ (30)

where $\gamma = \delta \|B\|$, $\delta = \delta_\Phi + \delta_\Omega$, $Y_{e\theta} = -(\Pi B)^{-1}\Pi A\Xi$
$\dot{V} = \Sigma^T \Pi (A\Xi + BY + \Phi + E)$

$= \Sigma^T \Pi (A\Xi \quad B(\Pi B)^{-1}\Pi A\Xi - B (\gamma+\eta)\sigma \gamma v(\Sigma^T\Pi B)^T + \Phi + E)$
$= \Sigma^T \Pi (-B(\gamma+\eta)\sigma \gamma v(\Sigma^T\Pi B)^T + \Phi + E)$
$= \Sigma^T \Pi B(-(\gamma+\eta)\sigma \gamma v(\Sigma^T\Pi B)^T) + \Sigma^T\Pi(\Phi+E)$
$= -\eta\|\Sigma^T\Pi B\| - \gamma\|\Sigma^T\Pi B\| + \Sigma^T\Pi(\Phi+E)$
$= -\eta\|\Sigma^T\Pi B\| - \gamma\|\Sigma^T\Pi B\| (1 \quad (\Sigma^T\Pi(\Phi+E))/\gamma\|\Sigma^T\Pi B\|)$
$< -\eta\|\Sigma^T\Pi B\|$

Λετ $K=\eta+\gamma$ (Εθυατιον 30) ανδ τηε χοντρολ φορχε $Y = Y_{e\theta}\ Κσγν(\Sigma^T\Pi B)^T$. Σταβιλιτψ χαν βε οβταινεδ ωηεν

$$K \ge \eta + \delta / \|B\|$$ (31)

where $\| \|$ denotes the Euclidean norm. Since PB is a constant matrix, $\overline{S}$ be used to represent $S^T PB$.

A disadvantage of the control law given in Equation (30) is that it is discontinuous and tends to excite the high frequency modes of the plant, also called the controlled system. The problem can be alleviated using a fuzzy inference mechanism.

A fuzzy inference mechanism is used to estimate the second part of Equation (30), that is, u_f. The range of u_f obtained from Equation (31) is [-K, K]. The fuzzy rule is (Chen, 2006).

If $\overline{S}$ is PB and $\overline{S}$ ' is PB, then u_f is NB.

PB: Positive Big; NB: Negative Big

All the rule bases are listed in Table 1. The characteristic $U=f(\overline{s})$ of the sliding mode controller with a boundary layer is linear, while that of the fuzzy sliding mode controller is nonlinear. The fuzzy sliding mode controller determines different actions for different $\overline{s}$ regions. For example, the fuzzy sliding mode controller uses slow reaction control for small $\overline{S}$ values, and quick control for large $\overline{S}$ values.

In existing studies concerning the membership functions of controlled systems, various types of fuzzy numbers are suggested for use, such as trapezoidal, triangular, and Gaussian functions (Chen et al., 2004, 2007; Hsiao et al., 2005) and the references therein). For convenience, the triangular membership function is used for each fuzzy number in this paper. Fuzzy output u_f can be calculated based on the center of the area of dufuzzification (Hsiao et al., 2005)

$$u_f = \frac{\sum_{i=1}^{l} w_i c_i}{\sum_{i=1}^{l} w_i} = \frac{[c_1 \ \cdots \ c_l]\begin{Bmatrix} w_1 \\ \vdots \\ w_l \end{Bmatrix}}{\sum_{i=1}^{l} w_i} = v^T \psi$$ (32)

where $v = [c_1 ..... c_l]$ denotes a adjustable parameter vector; c_i represents the center of the consequent part of the membership function; and w_i represents the firing strength of the ith rule. Meanwhile $\psi = \dfrac{[w_1 .... w_l]}{\sum_{i=1}^{l} w_i}$ is a firing strength vector.

From Equation (29), we see that the sliding mode controller requires an upper bound to the uncertainty. When the uncertainty increases, the control cost also increases. However, the optimal value of the uncertainty cannot be precisely obtained owing to a lack of knowledge regarding the structure or system complexity. Therefore, an adaptive fuzzy control is developed to deal with the problem and to estimate the minimum control cost.

Assume that there exists a specific $\hat{u}_f$ which achieves the minimum control cost and that $\hat{u}_f$ satisfies the sliding mode condition.
From Equation (32), $\hat{u}_f$ can be rewritten as follows:

$$\hat{u}_f = \hat{v}^T$$ (33)

where $\hat{v}$ denotes the optimal vector with which the minimum control cost is achieved.
Define the parameter vector as:

$$\tilde{v} = v - \hat{v}$$ (34)

Let the Lyapunov function for each controller be

$$V = \frac{1}{2}(\overline{s}^2 + \frac{1}{\alpha}\tilde{v}^T\tilde{v})$$ (35)

where α is a positive constant. Now,

$$\dot{V} = \overline{s}\ Pb_i u_f + \overline{s}\ P(F+E) + \frac{1}{\alpha}\tilde{v}^T\dot{v}$$

Table 1. Rule base of the adaptive sliding mode controller.

$\overline{S}\,'\setminus\overline{S}$	PB	PM	PS	Z	NS	NM	NB
PB	NB	NB	NM	NS	NS	Z	Z
PM	NB	NM	NM	NS	Z	Z	PS
PS	NM	NM	NS	NS	Z	PS	PS
Z	NM	NS	NS	Z	PS	PS	PM
NS	NS	NS	Z	PS	PS	PM	PM
NM	NS	Z	Z	PS	PM	PM	PB
NB	Z	Z	PS	PS	PM	PB	PB

PB: Positive Big; PM: Positive Medium; PS: Positive Small; Z: Zero; NB: Negative Big; NM: Negative Medium; NS: Negative Small.

$$= \overline{s}\,Pb_i(u_r\,\hat{u}_f)+\overline{s}\,Pb_i\hat{u}_f+\overline{s}\,P(F+E)+\frac{1}{\alpha}\,\widetilde{v}^{\,T}\dot{v}$$

$$= \overline{s}\,Pb_i(\varpi^T-\hat{v}^T)\psi+\overline{s}\,\Pi\beta_i\hat{u}_f+\overline{s}\,\Pi(\Phi+E)+\frac{1}{\alpha}\,\widetilde{v}^{\,T}\dot{v}$$

$$= \overline{s}\,\Pi\beta_i\widetilde{v}^{\,T}\psi+\overline{s}\,\Pi\beta_i\hat{u}_f+\overline{s}\,\Pi(\Phi+E)+\frac{1}{\alpha}\,\widetilde{v}^{\,\square}\dot{v}$$

$$= \frac{1}{\alpha}\,\widetilde{v}^{\,T}(\dot{v}+\alpha\overline{s}\,\Pi\beta_i\psi)+\overline{s}\,\Pi\beta_i\hat{u}_f+\overline{s}\,\Pi(\Phi+E)$$

$$<-\eta_i|\,\overline{s}\,\Pi\beta_i/(\,\hat{u}_f \text{ σατισφιεσ τηε σλιδινγ μοδε χονδιτιον ανδ λετ } \dot{v}=-$$

$$\alpha\,\overline{s}\,\Pi\beta_i\psi). \text{ Φιναλλψ, τηε αδαπτιϖε λαω οβταινεδ ισ } \dot{v}=-\alpha\,\overline{s}\,\Pi\beta_i$$
(36)

The adaptive law adjusts the centers of the membership function of the consequent part. This adaptive law is derived from Lyapunov theory, so $V \rightarrow 0$ as $t \rightarrow \infty$. IF $V \rightarrow 0$, then $\widetilde{v} \rightarrow 0$. As $\widetilde{v} \rightarrow 0$, the minimum control cost $\hat{u}_f$ can be achieved. The design procedure for the AFSMC can be briefly summarized as follows:

Step 1:   Determine the state and control variables.
Step 2:   Use the optimal sliding modes method to determine the sliding surface.
Step 3:   Select thickness of the boundary layer based on the allowable responses.
Step 4:   Calculate the value of K according to Equation (31)
Step 5:   Define the fuzzy sets for both the input and output of the fuzzy inference mechanism.
Step 6: Perform on-line AFSMC.

Some examples are used to illustrate the AFSMC for LRB isolated buildings. Here we examine the application of AFSMC to prevent extreme earthquake induced oscillations of the building. The proposed AFSMC can be easily applied in multiple degrees-of-freedom systems. A six based-isolated building involving oscillations is simulated to demonstrate the effects discussed in this study.

NUMERICAL SIMULATION AND RESULTS

The AFSMC is applied to control the building with LRB isolators. An   base-isolated six floor building is illustrated in Figure 1. The nominal values of each floor

mass, base mass, stiffness of each floor, and damping ratio are 345600 kg, 450000 kg, 3.1e8 N/m, and 0.02, respectively. Moreover, the nominal value of LRB elastic stiffness is 9.6e6 N/m, the LRB yield stiffness is 1.968e6 N/m and the yielding deformation D_y is 1 cm. The optimal sliding mode method is used to determine the sliding surface with a diagonal weighting matrix Q; Q_{77} =0.01 Q_{ii} = 5e5, for i= 1, 2....6 and Qii= 1. for l = 8, 9....14. and Q_{33} = Q_{44} = 1. This fuzzy controller has 49 fuzzy rules, as listed in Table 1. The triangular membership function is used for each fuzzy number. $f(t)$ are determined by Equations (3) and (4). The parametric values are as follows: k_b= 9.6e3; D_y = 1 cm;α= 1;β=γ= 0.5 and η=3.The AFSMC discussed in this paper are compared using real earthquake data, consisting of acceleration records from Chi Chi (1999) earthquakes.

The acceleration records of the Chi Chi earthquake are shown in Figure 3. The base and six floor displacements of the considered building after the application of AFSMC are indicated in Figures 4 and 5. The relationship between the LRB shear force and deformation with no control, and AFSMC, is shown in Figure 6. The maximum response quantities of the building with LRB isolation, excited by Chi Chi earthquake acceleration, are listed in Table 2.

As shown in the Figures 3 to 6, AFSMC controller suppresses the earthquake induced vibrations. The maximum displacement, control force and acceleration responses of the considered isolated-building (with and without the controllers) are all shown in Tables 2. The results show that the AFSMC performs excellent responses s as well as more effective control forces. These results indicate that the proposed controller is an effective method for seismic isolation of structures.

The effectiveness of this algorithm is further demonstrated by the simulation results for a long-period artificial earthquake, scaled to have a peak ground acceleration of 0.3 g as the input excitation. The time history of the long-period artificial earthquake is displayed in Figure 7. The frequencies of these artificial earthquakes are shown in Figure 8. The maximum
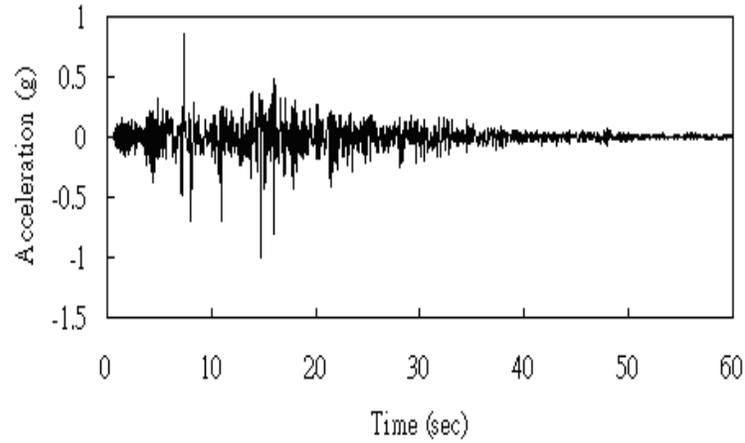
Figure 3. Acceleration records for the Chi Chi earthquake.
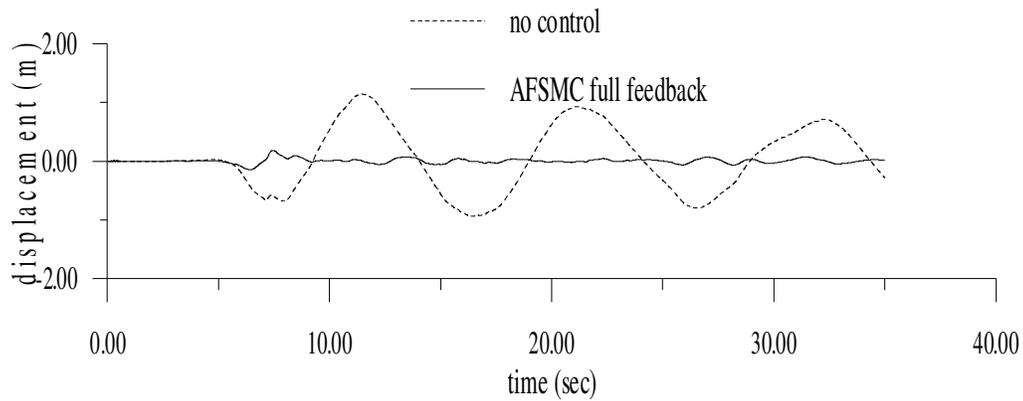
Figure 4. AFSMC controlled and uncontrolled base displacement history.
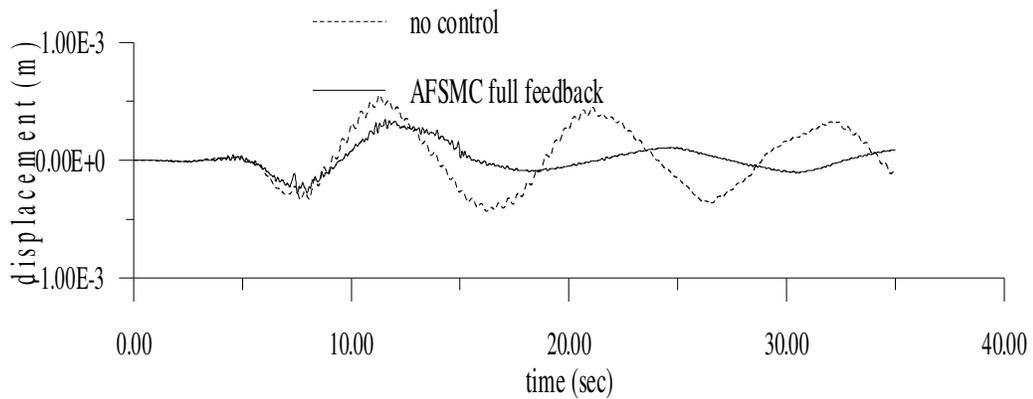
Figure 5. AFSMC controlled and uncontrolled six floor displacement history.

response quantities of the buildings for the simulated earthquakes are listed in Table 3. Compared to the case without control, the building displacement and the shear force of LRB are significantly reduced. This phenomenon demonstrates that the adaptive fuzzy sliding mode control works well with long-period contents.
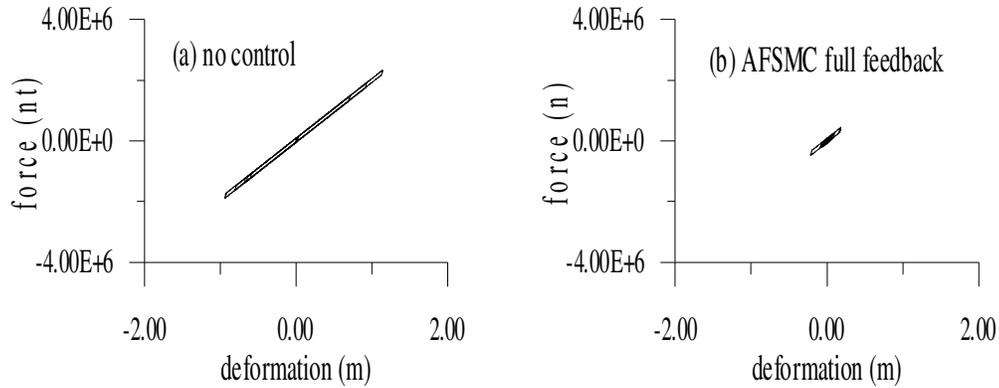
Figure 6. Relationship of LRB shear force and deformation.

Table 2. Maximum response quantities of building with LRB isolation.

	No control, U$_{max}$ = 0 kN		AFSMC control, U$_{max}$ = 2152 kN	
	x_i(m)	$\ddot{x}_i$ (m/s^2)	x_i(m)	$\ddot{x}_i$ (m/s^2)
B	1.12	5.32E-01	1.72E-01	3.07E-01
1	3.09E-03	5.29 E-01	1.73E-03	3.05E-01
2	2.74E-03	5.30 E-01	1.58E-03	3.03E-01
3	2.29E-03	5.24 E-01	1.25E-03	3.00E-01
4	1.75E-03	5.31 E-01	8.06E-04	3.04E-01
5	1.17E-03	5.27 E-01	5.27E-04	2.99E-01
6	5.52E-04	5.28 E-01	3.43E-04	2.97E-01
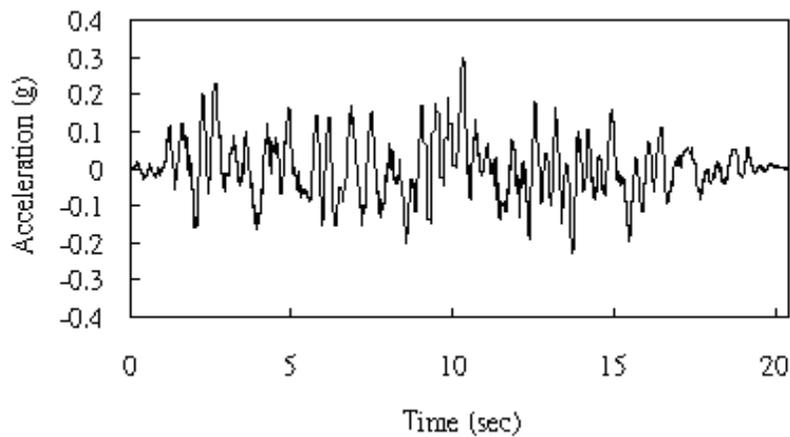
Figure 7. Time history of the long-period artificial earthquake.

Conclusions

In this study we develop an efficient adaptive fuzzy sliding mode control (AFSMC) algorithm for stability problems in buildings constructed with lead rubber bearing (LRB) isolation hybrid protective systems. The simulation results indicate that a building equipped with an LRB isolation system has reduced base displacement relative to the ground, and the absolute acceleration. Moreover, AFSMC can reduce the floor displacement and all of the aforementioned response quantities. The maximum control forces of he AFSMC
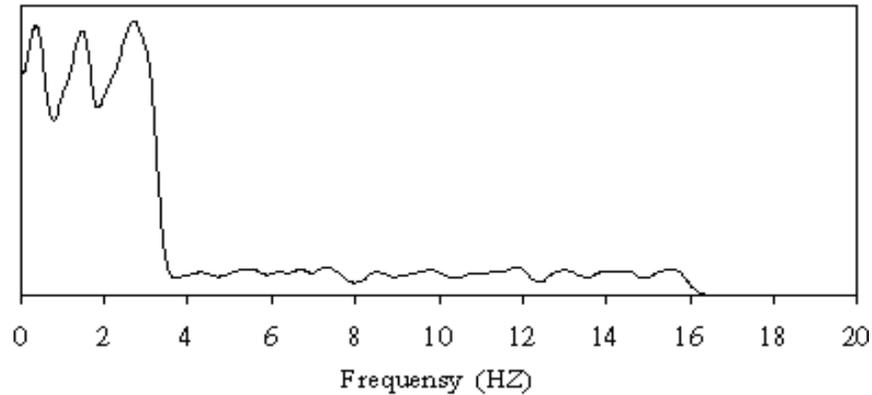
Figure 8. Frequency content of the long-period artificial earthquake.

Table 3. Maximum response quantities of building with LRB isolation.

	LRB (no control), U_{max}= 0 kN		LRB (AFSMC control), U_{max} = 2143 kN	
	x_i(m)	$\ddot{x}_i$ (m/s^2)	x_i(m)	$\ddot{x}_i$ (m/s^2)
B	2.16	9.66E-01	5.85E-01	4.24E-01
1	5.31E-03	9.65E-01	3.05E-3	4.22E-01
2	4.42E-03	9.53E-01	2.53E-03	4.20E-01
3	3.52E-03	9.58E-01	2.04E-03	4.17E-01
4	2.59E-03	9.56E-01	1.56E-03	4.03E-01
5	1.65E-03	9.65E-01	1.05E-03	4.21E-01
6	9.90E-04	9.64E-01	5.56E-04	4.22E-01

are relatively low, all being less than 11% of the superstructure weight. The results in Table 3 reveal that the adaptive fuzzy sliding mode control is not sensitive to long-period contents. The effectiveness and feasibility of the proposed controller design method is demonstrated using numerical simulations of seismically excited buildings with LRB isolation. The example demonstrates that the proposed methodology can be applied to practical control systems. Besides reducing oscillations that could be considered in the AFSMC approach, some important issues still remain open, such as stability analysis, stabilization problems and the control performance. Here, the focus is on the development of the AFSMC for seismically excited buildings. The proposed control strategies could be extended to time-delay problems and time-varying multi-floor structures in future. Another direction for future research would be to extend the proposed control strategies to time-varying tall building   structures.

ACKNOWLEDGEMENT

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